A NEW METHOD FOR TESTING THE RF SURFACE RESISTANCE OF NEG COATED VACUUM TUBES AT 0.36 - 4.6 GHz

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Abstract

This paper explores a new technique for testing the RF resistivity of Non-Evaporable Getter (NEG) thin films. The technique can be applied to tubular samples, which are representative of the beamlines that would be coated within accelerators, and can also be used for pumping property measurements, so a full analysis of NEG coating properties can be made, and a NEG composition with best compromise between resistivity and pumping can be found. The technique allows measurement of RF surface resistance at 0.36 – 4.65 GHz. The method was used on uncoated samples of stainless steel and Cu, to demonstrate a clear difference in measured surface resistance, and samples coated with single element Ti NEG. Samples were coated with approximately 3 µm thickness, with the columnar NEG coating showing no difference in surface resistance, and dense NEG coating showing a variation in surface resistance from the copper substrate.

INTRODUCTION

Accelerators need to meet a number of specifications to be able to produce a good usable beam for experiments. For example, they need a residual gas pressure below a certain value to ensure the beam does not get interrupted by beam-gas interactions, as well as beamlines with high electric conductivity to ensure the wakefields generated by the beam are not exacerbated, which would have adverse effects, such as increasing the beam's energy spread or emittance.

Non evaporable getter (NEG) coatings are used in accelerators world-wide to provide a specified vacuum within accelerator beam chamber [1–3], but to the detriment of the beam tube RF electrical conductivity. Although NEG coatings provide a lower outgassing and a distributed pumping effect along the beam, they also have a higher resistivity than copper or aluminium.

To provide the experimental data for wakefield analysis of NEG coated beam chambers, previous studies [4] have been performed on the RF resistivity measurements at 7.8 GHz on dense and columnar NEG coatings of various thicknesses, with the conclusion being drawn that: (a) the bulk conductivity (σ) of NEG coatings can vary in a wide range from $\sigma = 1.4 \times 10^4$ S/m for the columnar NEG coating to $\sigma = 8 \times 10^5$ S/m for the dense NEG coating, (b) RF surface resistance (R_s) increases with NEG thickness from the value of the bulk substrate to a value for a bulk NEG coating.

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Since the RF measurements were performed at a single frequency $f = 7.8$ GHz, the frequency dependence behaviour of R_s was initially modelled with Eq. (22) in Ref. [4]:

$$R_s = R_{NEG} \frac{1 - \exp(-4\kappa d) + 2\sin(2\kappa d) + \exp(-2\kappa d)}{1 - \exp(-4\kappa d) - 2\sin(2\kappa d) - \exp(-2\kappa_1 d_1)}, \quad (1)$$

where NEG and copper RF resistance for bulk material surface $R_{NEG} = \sqrt{(\omega\mu_0)/(2\sigma_1)}$ and $R_{Cu} = \sqrt{(\omega\mu_0)/(2\sigma_{Cu})}$ were calculated with bulk conductivities of NEG and copper σ_{NEG} and σ_{Cu}, respectively, wavenumber $\kappa = \sqrt{(\omega\mu_0\sigma_{NEG}/2)}$, NEG thickness d, and the surface resistance mismatch $\delta = (R_{NEG} - R_{Cu})/(R_{NEG} + R_{Cu})$.

The results of modelling are shown in Fig. 1 (and in Fig. 4 in Ref. [5]). The results for bulk copper (Cu) with $\sigma_{Cu} = 4.5 \times 10^7$ S/m and stainless steel (SS) with $\sigma_{SS} = 1.0 \times 10^6$ S/m follow a skin depth model expecting $R_s(f) \propto \sqrt{f}$.

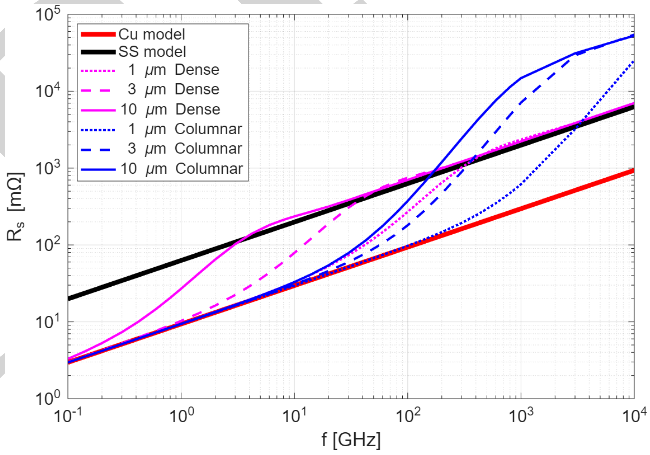

Figure 1: RF surface resistance as a function of frequency $R_s(f)$ calculated with Eq. 1 for bulk copper (Cu) and stainless steel (SS), and for copper coated with dense and columnar NEG film with thicknesses of 1, 3 and 10 µm.

This model showed that using a NEG coating with very low thickness has negligible effect of conductivity of the substrate material. However, this lower thickness reduces the effectiveness of the pumping properties, with a lower lifetime due to the lower capacity of the NEG [6, 7].

The aim of this study is to measure $R_s(f)$ at 0.36 - 4.65 GHz, on tubular samples. With this capability, NEG coated samples could be deposited, and both the pumping properties and surface resistance could be measured, to understand the full spectrum of the coatings properties.

METHODOLOGY

To measure R_s of the NEG coatings, a coaxial resonator was created inside the sample tube by inserting an inner conducting electrode aligned coaxially with the tube [8]. The central electrode is held in the centre of the tube by two hollow PTFE pieces screwed to each end, see Fig. 2. The couplers are located at either end of the tube.

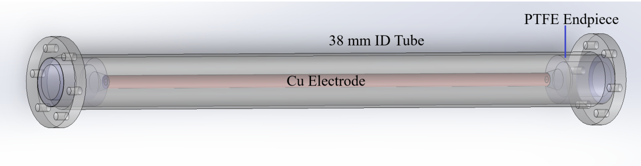

Figure 2: Schematic of the internal structure used for R_s tests, showing the coaxial copper rod and PTFE endpieces.

Simulations

RF modelling was carried out using the eigenmode solver in CST [9]. The model (Fig. 3) comprised a cylindrical tube with $\sigma_t = 5.9 \times 10^7$ S/m (Cu) or $\sigma_t = 1.3 \times 10^6$ S/m (SS), inner diameter $ID = 38$ mm and length $L_t = 500$ mm. A central Cu electrode with $\sigma_e = 5.9 \times 10^7$ S/m, ∅20 mm and $L_e = 400$ mm. Stainless steel (SS) end flanges with coaxial feedthroughs. PTFE endpieces with loss tangent $\tan\delta = 2 \times 10^{-4}$. The simulations were performed to evaluate the unloaded quality factor (Q_0) and the distribution of RF losses between components.

Coaxial resonant modes are observed from 0.36 to above 4 GHz, corresponding to TEM standing-wave modes with resonances occurring at integer multiples of half-wavelengths along the electrode length. Examples of representative modes (1, 7 and 13) are shown in Fig. 3, with corresponding Q_0 values and loss fractions summarised in Table 1. Replacing the SS tube with Cu increases Q_0 across all modes due to the lower R_s of the tube. This reduces the fractional tube losses and shifts the dominant RF dissipation to the central electrode. RF losses are dominated by metallic surface (central electrode and outer tube), while contributions from the end flanges are negligible. Although the contribution from the PTFE loss increases with mode number due to enhanced electric field interaction, it remains a minor contribution and does not dominate the overall dissipation.

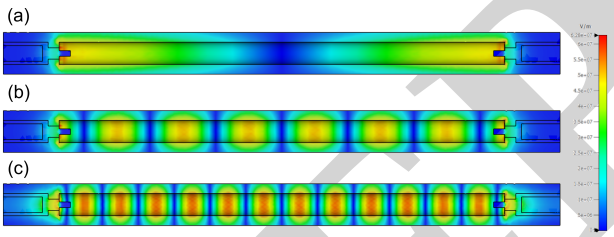

Figure 3: The CST model of the coaxial resonator showing the electric field distributions for three representative modes: (a) 0.362, (b) 2.528 and (c) 4.647 GHz.

Table 1: Simulated Q_0 and Fractional RF losses for Modes 1, 7 and 13, Comparing Cu and SS Tubes

Mode	f [GHz]	**Tube**	Q_0 ($\times 10^3$)	**Rod** [%]	**Tube** [%]	**PTFE** [%]
1	0.36	Cu	2.4	64.5	35.1	0.5
		SS	0.8	21.3	78.6	0.2
7	2.53	Cu	6.4	63.4	34.9	1.7
		SS	2.1	21.0	78.5	0.6
13	4.65	Cu	8.5	57.9	34.5	7.3
		SS	2.8	19.3	78.1	2.4

Samples

The tubular samples used in this study were with $ID = 38$ mm and $L_t = 500$ mm. Initially, two sample tubes made of uncoated copper (Cu) and 316 LN stainless steel (SS) were measured to get a baseline of measurements for comparison.

Table 2: Deposition Parameters

Parameter	**Columnar-thin**		**Columnar-thick**		**Dense-thick**
d [µm]	1		3		3
Mode	Pulsed	DC	Pulsed	DC	Pulsed
Power [W]	50	50	50	50	50
I [A]	0.17	0.28	0.18	0.27	0.19
V [V]	295	177	273	185	266
B [G]	350	350	350	350	350
P [Pa]	5	75	6.1	60	6.1
t [hrs]	1	5	1	20	21

Then, cylindrical magnetron sputtering (described in [10]) was used to deposit three Cu tubes with Ti thin-film, which is a single element NEG coating. Deposition properties are described in Table 2. Coating thickness has been estimated by experience from previous samples deposited with similar deposition parameters. During deposition, copper foil at the end of each tube was used as witness samples to investigate the sample structure using a scanning electron microscope.

RF Measurements

The open ends of the samples were closed with CF40 flanges each containing a central N-type RF feedthrough. The inner electrode was a copper rod with ∅20 mm and a $L = 400$ mm. The feedthroughs were connected via 3 m long coaxial cables to ports 1 and 2 on a vector network analyser (VNA, Keysight P5024A). The coaxial cables were manually calibrated using an N-type calibration kit.

RESULTS

Figure 4 shows the cross-section of the dense NEG coating taken from the witness sample. From this, the thickness can

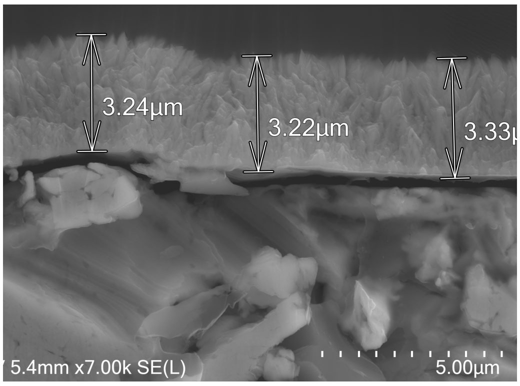

Figure 4: An SEM cross-sectional image of the Dense NEG coating.

be seen to be 3.2 µm. This aligns with our thickness estimates in Table 2.

Figure 5 shows results obtained from the 5 samples. The RF surface resistance is shown as a function of applied frequency. This figure also includes the data obtained earlier on planar samples at $f = 7.8$ GHz in Ref. [4]. The results of the model from Fig. 1 are also shown to compare to the experimental data.

There is a clear difference between stainless steel and copper samples. The frequency dependence for bare stainless steel and copper fit linearly with the square root of frequency, as expected.

The result for copper sample coated with a columnar 1 and 3 µm thick NEG film is consistent with the bare copper sample, following the model in Fig 1.

The result for copper sample coated with a dense 3 µm thick NEG film show surface resistance increases with frequency faster than for bulk copper. This is also consistent with a model.

DISCUSSION

The results demonstrate that R_s for stainless steel and for copper samples can be easily measured via this method. Calculated bulk conductivity for stainless steel is $\sigma_{SS} = 1.0 \times 10^6$ S/m, and for copper is $\sigma_{Cu} = 4.5 \times 10^7$ S/m.

From our previous experiments [4] for bare and 6 µm columnar NEG coated copper, the surface resistance is measured as 28 and 34 mΩ. These results are well fitted with the model in Eq. 1, and show that for NEG coating with thickness up to 6 µm, there will be no significant effect of RF resistance in a frequency range between 0.36 – 7.8 GHz. This is consistent with the results shown in Fig. 5. For 4.7 µm dense NEG coating, the same paper reports surface resistance of 111 mΩ. This is also reflected in Fig. 5, where the dense NEG coating measured with this method has increased the surface resistance compared with bulk copper.

These results also show that the method is sensitive enough to measure impact of any coatings on the top of copper in a frequency range of 0.36 and 4.65 GHz. The results obtained with this technique can be directly applied for modelling RF resistive wakefield and its impact on bunch energy spread. Together with measurements of pumping properties, which are most commonly measured on the tubular samples this method is designed for, a full spectrum of NEG coating properties can be collected.

In future work, more samples will be produced with single, dual, triple and quadruple NEG alloys, and conductive NEG alloys will be studied.

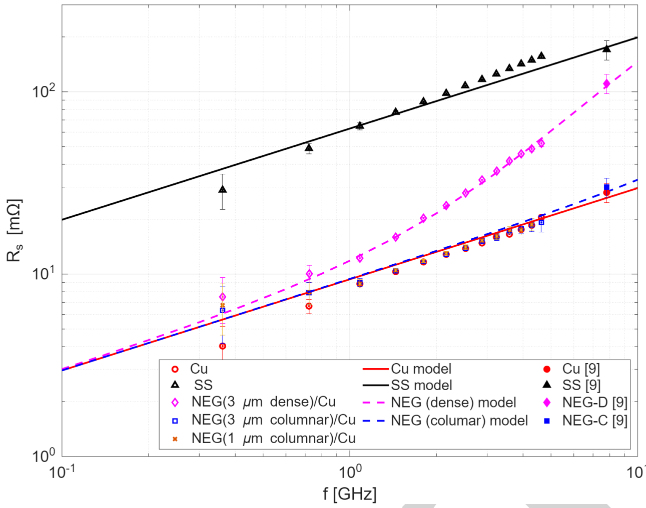

Figure 5: Experimental and modelling results for $R_s(f)$: for bulk copper (Cu) and stainless steel (SS), and for copper coated with 3 µm thick dense and 1 and 3 µm thick columnar NEG films.

CONCLUSION

This paper has explored a new method for testing the resistance of thin-film NEG coatings. The measurements were performed in the frequency range from 0.36 to 4.65 GHz.

A comparison between bare and coated samples of copper and stainless steel, and copper coated with columnar Ti thin film of approximately 1 and 3 µm and copper coated with dense Ti thin film of approximately 3 µm has been shown.

The results show the method is clearly able to differentiate surface resistance between different substrate material (i.e stainless steel and copper). It shows that 3 µm thick columnar NEG coating does not increase the RF surface resistance of copper in the frequency range from 0.36-4 GHz, which is in accordance with our earlier measurements at 7.8 GHz and our model. 3 µm thick dense NEG is shown to cause a deviation in surface resistance compared with bare copper. This again is in line with our earlier measurements at 7.8 GHz.

Future measurements will be applied to copper tubes coated with NEG with various thicknesses, chemical composition, structure and morphology.

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